STUDY OF Λ-HYPERNUCLEI WITH ELECTROMAGNETIC PROBES AT JLAB

Liguang Tang

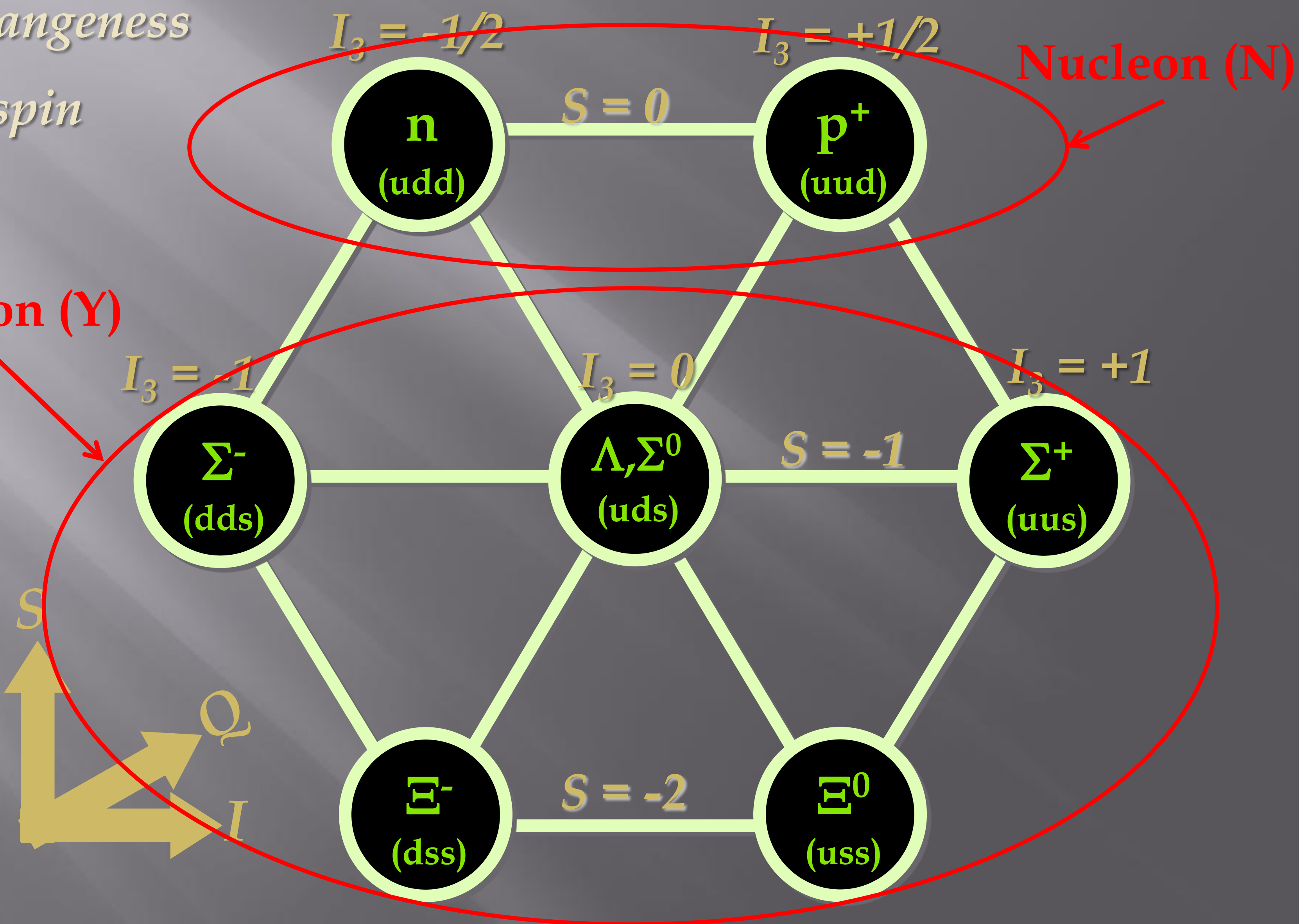
Department of Physics, Hampton University
&
Jefferson National Laboratory (JLAB)

July 28 - 30, 2010, Hadron Physics 2010, Tsinghua University

Introduction – $J^p=1/2^+$ Baryon Family

S - Strangeness

I - Isospin



$I_3 = -1/2$

$I_3 = +1/2$

Nucleon (N)

n (udd)

$S = 0$

p^+ (uud)

Hyperon (Y)

$I_3 = -1$

$I_3 = 0$

$I_3 = +1$

Σ^- (dds)

Λ,Σ^0 (uds)

$S = -1$

Σ^+ (uus)

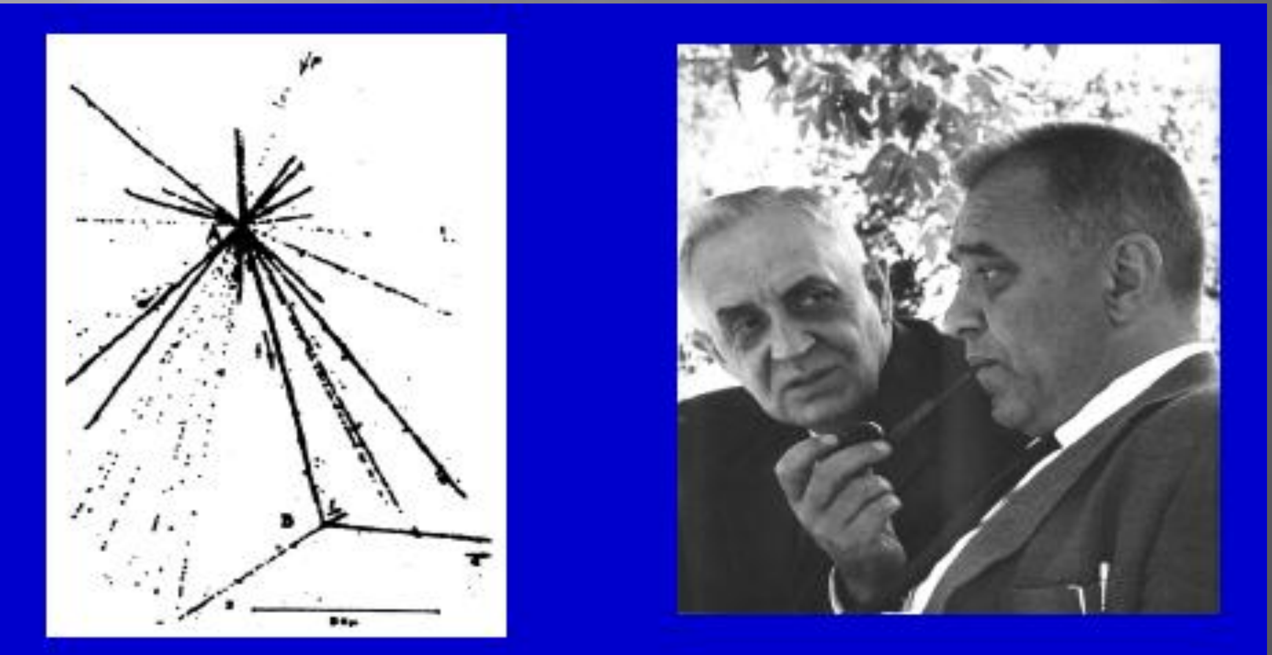
Ξ^- (dss)

$S = -2$

Ξ^0 (uss)

Introduction – *Hypernuclei*

- *A nucleus with one or more nucleons replaced by hyperon, Λ, Σ, …*
- *Since first hypernucleus found 50 some years ago, hypernuclei have been used as rich laboratory to study YN and YY interactions*



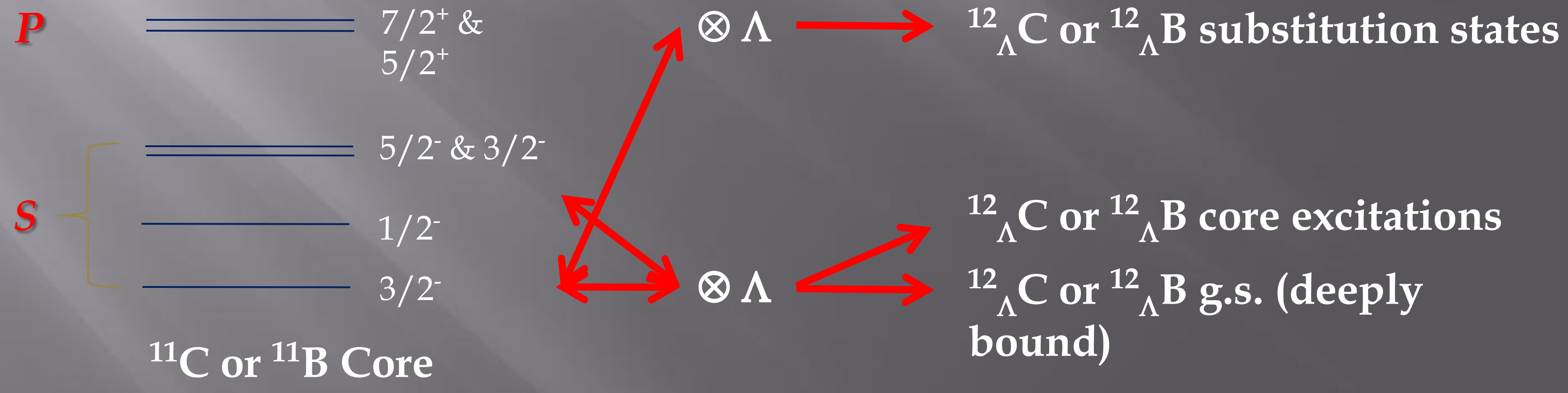
Discovery of the first hypernucleus by pionic decay in emulsion produced by cosmic rays, *Marian Danysz* and *Jerzy Pniewski*, 1952

Introduction – *Λ-Hypernuclei*

- Sufficient long lifetime, g.s. *Λ-hypernucleus* decays only weakly via *$\Lambda \to \pi N$ or $\Lambda N \to NN$,* thus mass spectroscopy with narrow states *(<few to 100 keV)* exists
- Description of a Λ-hypernucleus within two-body frame work – Nuclear Core (Particle hole) ⊗ Λ (particle):

(Few example states)

(Example of the lowest mass states)



P

$7/2^+$ & $5/2^+$

$5/2^-$ & $3/2^-$

S

$1/2^-$

$3/2^-$

^{11}C or ^{11}B Core

⊗ Λ

⊗ Λ

$^{12}_{\Lambda}$C or $^{12}_{\Lambda}$B substitution states

$^{12}_{\Lambda}$C or $^{12}_{\Lambda}$B core excitations

$^{12}_{\Lambda}$C or $^{12}_{\Lambda}$B g.s. (deeply bound)

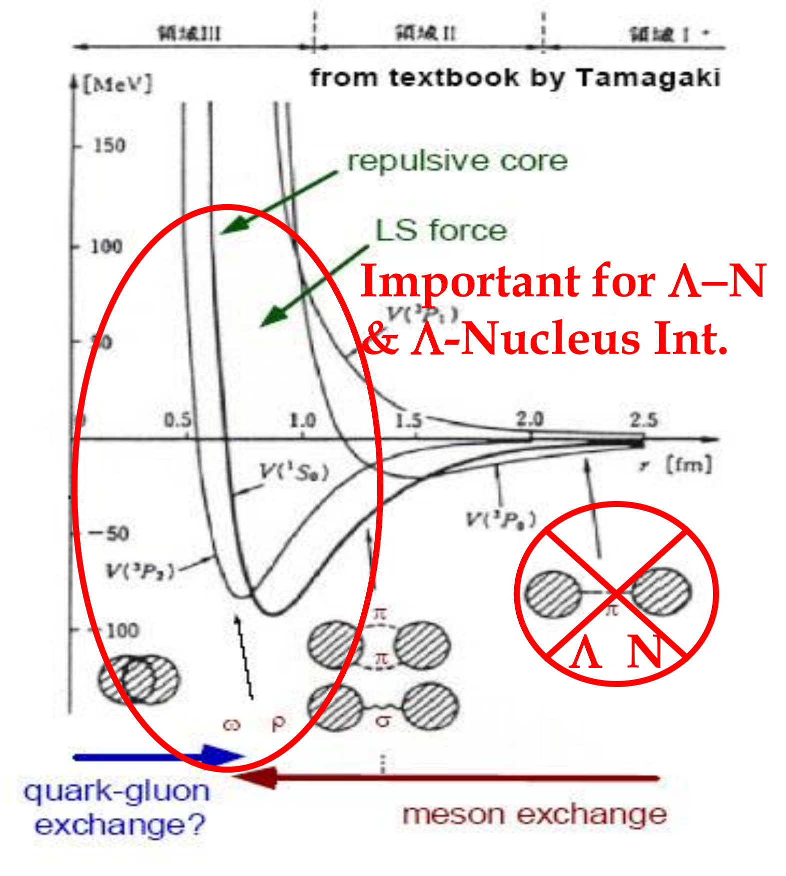
Introduction – *Λ-Hypernuclei* (cont.)

- Two-body effective *Λ-Nucleus* potential (Effective theory):

$$V_{\Lambda N}(r) = V_c(r) + V_s(r)(S_\Lambda \bullet S_N) + V_\Lambda(r)(L_N \bullet S_\Lambda) + V_N(r)(L_\Lambda \bullet S_N) + V_T(r)S_{12}$$

- The right *Λ-N and Λ-Nucleus* models must correctly describe the mass spectroscopy (*Λ binding energies, excitations, spin/parities, …)*

- A novel feature of *Λ-hypernuclei*
  - ***Short range interactions***
  - ***Change of core structures***
  - ***Baryonic property change***
  - ***No Pauli block – access to the full nuclear interioer***
  - ***Drip line limit***



Leading Issues

- Understand the level structures
- Charge symmetry breaking for YN interaction
- Spin – parity determination for the ground state
- Weak decay of hypernuclei

Hypernuclear Physics Programs at JLAB

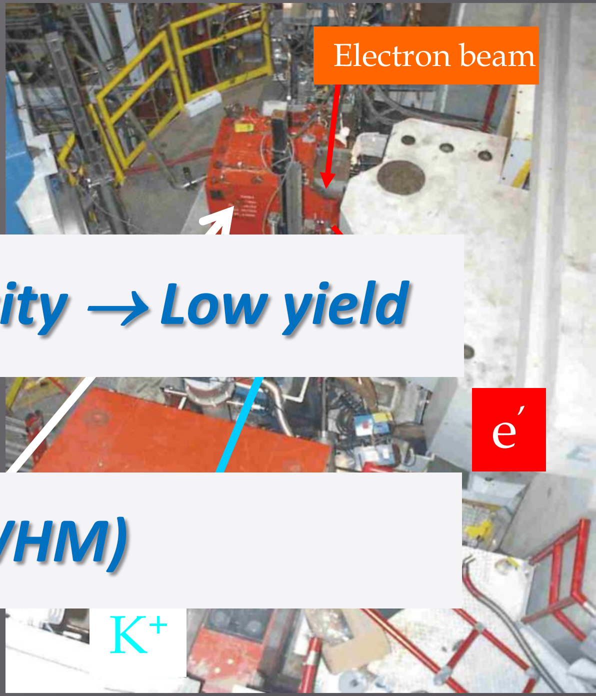
- Established: *High precision mass spectroscopy of Λ-hypernuclei with wide mass range. (Hall C program will be shown as an example)*
- Proposing: *High precision decay pion spectroscopy for light and exotic Λ-hypernuclei*

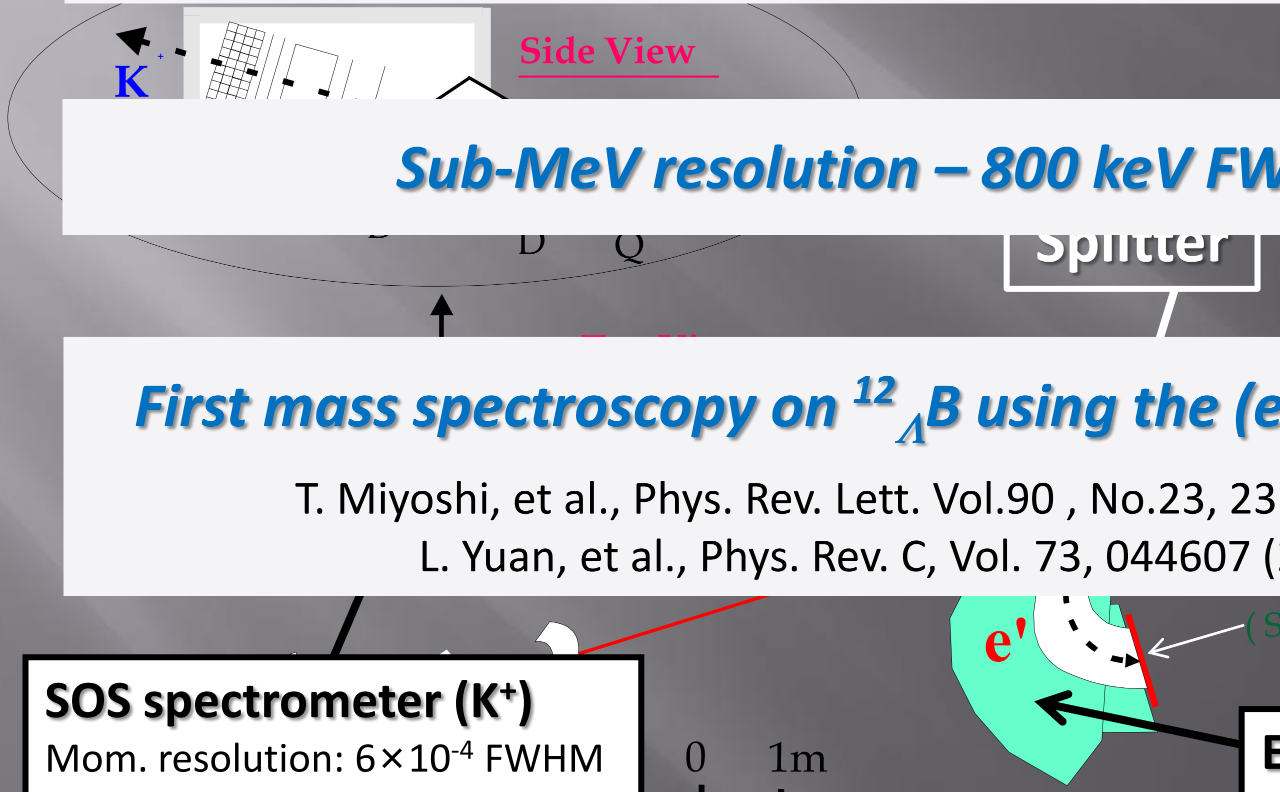
Hypernuclear Physics Programs in Hall C

- E89-009 (Phase I, 2000) – Feasibility
- Existing equipment
- Common Splitter – Aims to high yield

High accidental background → Low luminosity → Low yield

Sub-MeV resolution – 800 keV FWHM)





First mass spectroscopy on $^{12}_{\Lambda}$B using the (e, e'K$^+$) reaction

T. Miyoshi, et al., Phys. Rev. Lett. Vol.90 , No.23, 232502 (2003)
L. Yuan, et al., Phys. Rev. C, Vol. 73, 044607 (2006)

SOS spectrometer (K$^+$)
Mom. resolution: 6×10^{-4} FWHM
Solid angle acceptance : 5msr
Central angle: 2 degrees

ENGE Spectrometer (e')
Mom. resolution: 5×10^{-4} FWHM
Solid angle acceptance: 1.6msr

Hypernuclear Physics Programs in Hall C

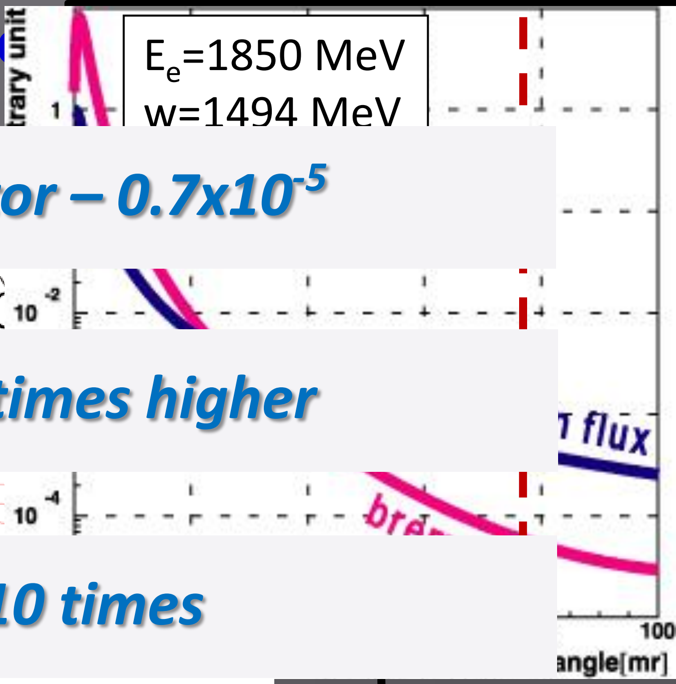
- **E01-011/HKS (Phase II, 2005) – First upgra**
- **Replaced SOS by HKS w/ new KID system**
-

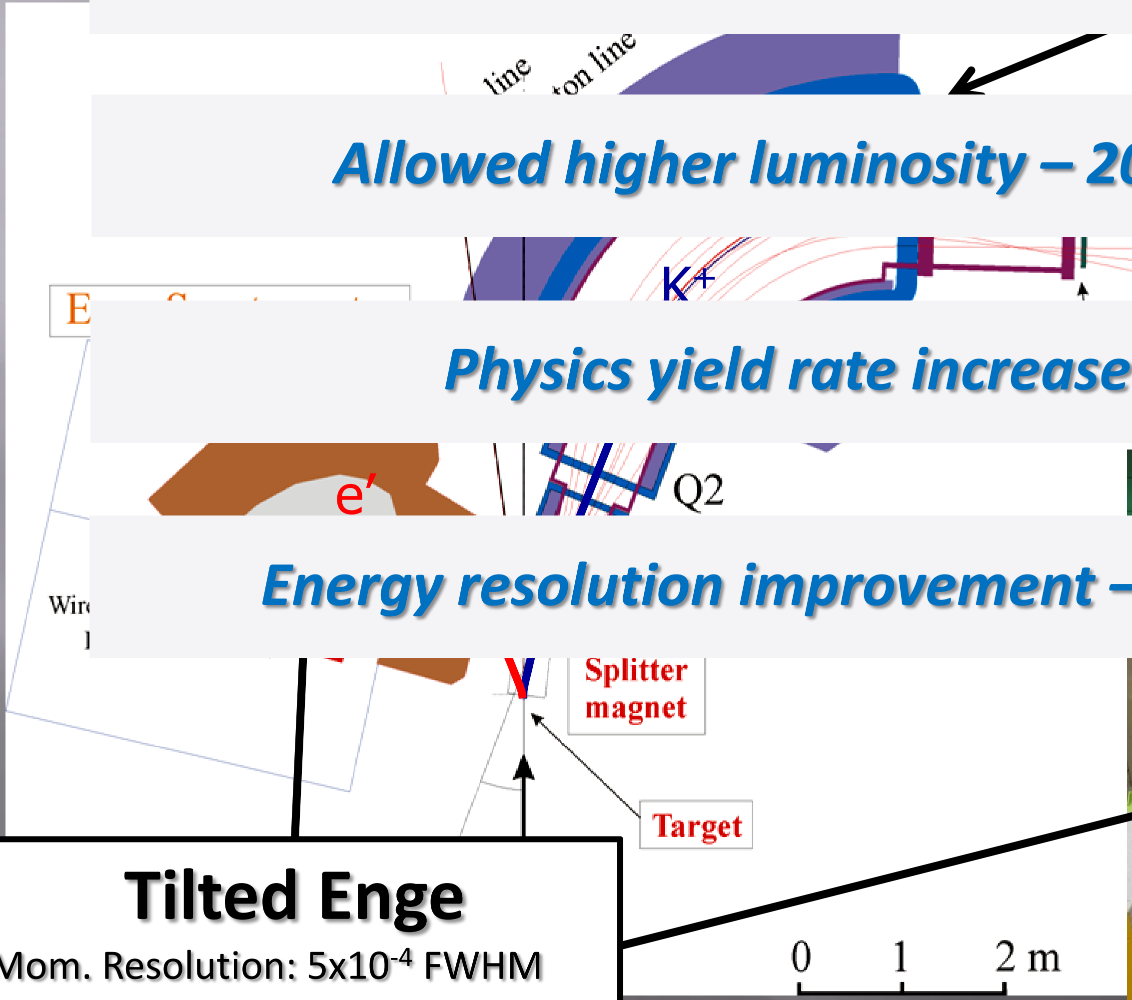
Electron single rate reduction factor – 0.7x10^{-5}

Allowed higher luminosity – 200 times higher

Physics yield rate increase – 10 times

Energy resolution improvement – ~450 keV FWHM





Tilted Enge

Mom. Resolution: 5x10^{-4} FWHM

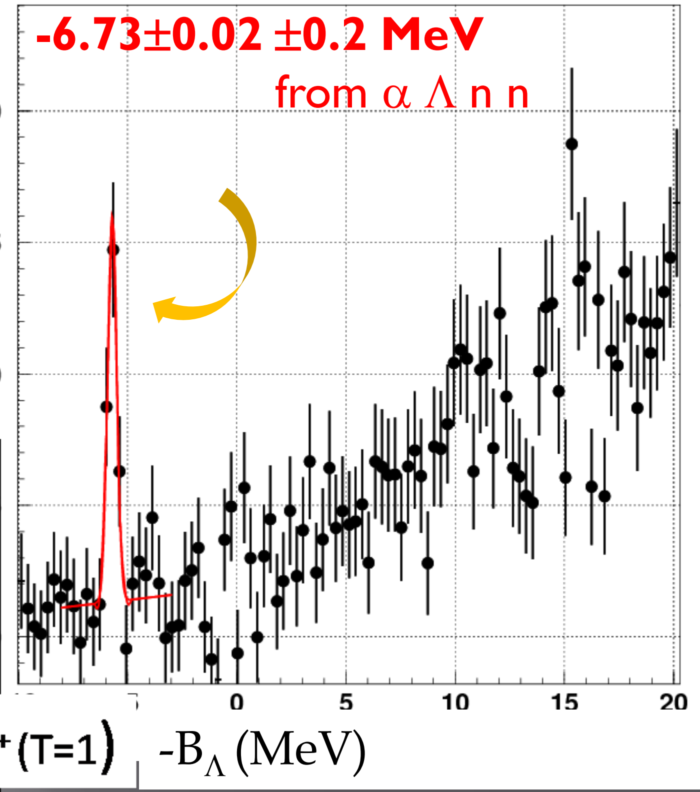
Scattering angle: ~4.5°

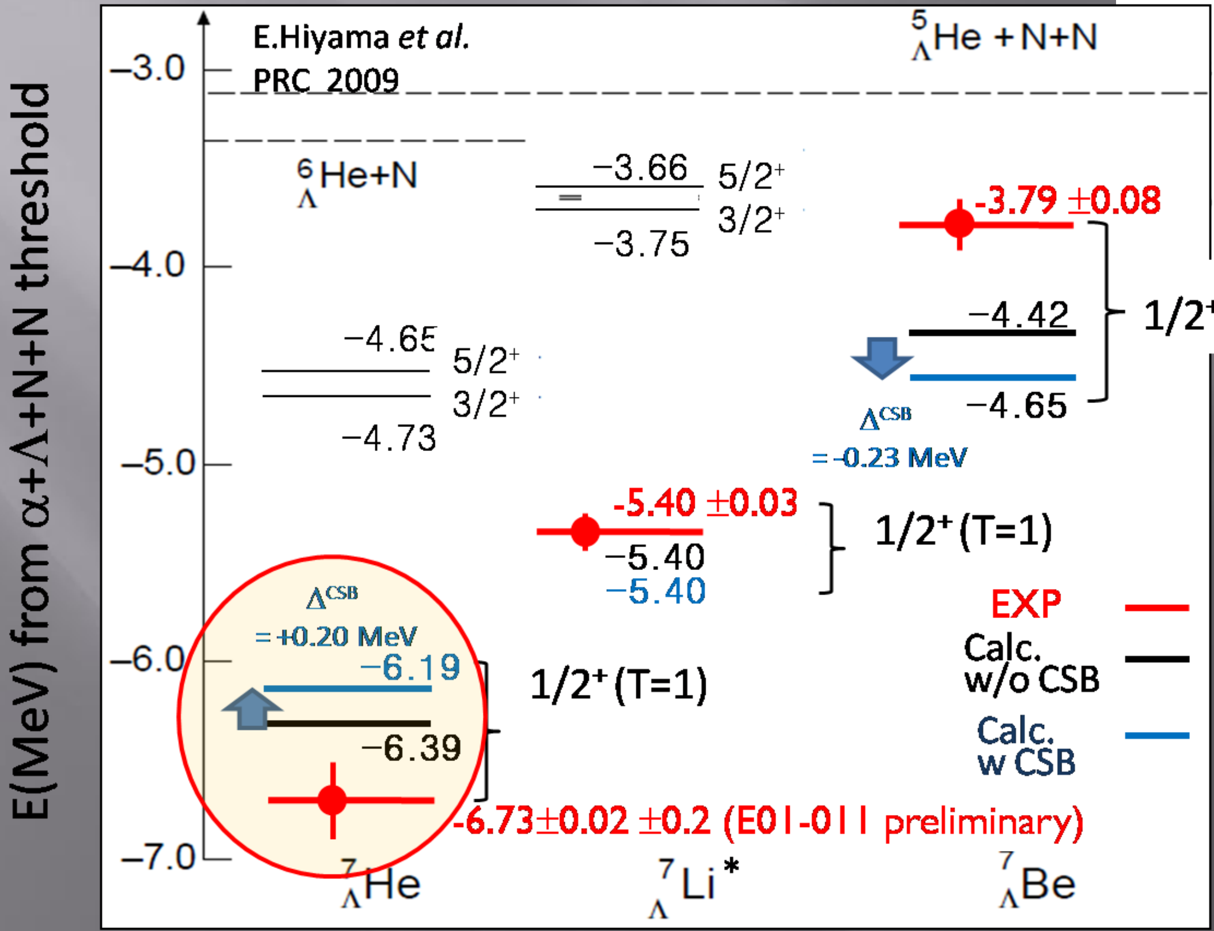
A Highlight of JLab E01-011 (HKS)

First reliable observation of ${}^{7}_{\Lambda}$He

Test of Charge Symmetry Breaking Effect.

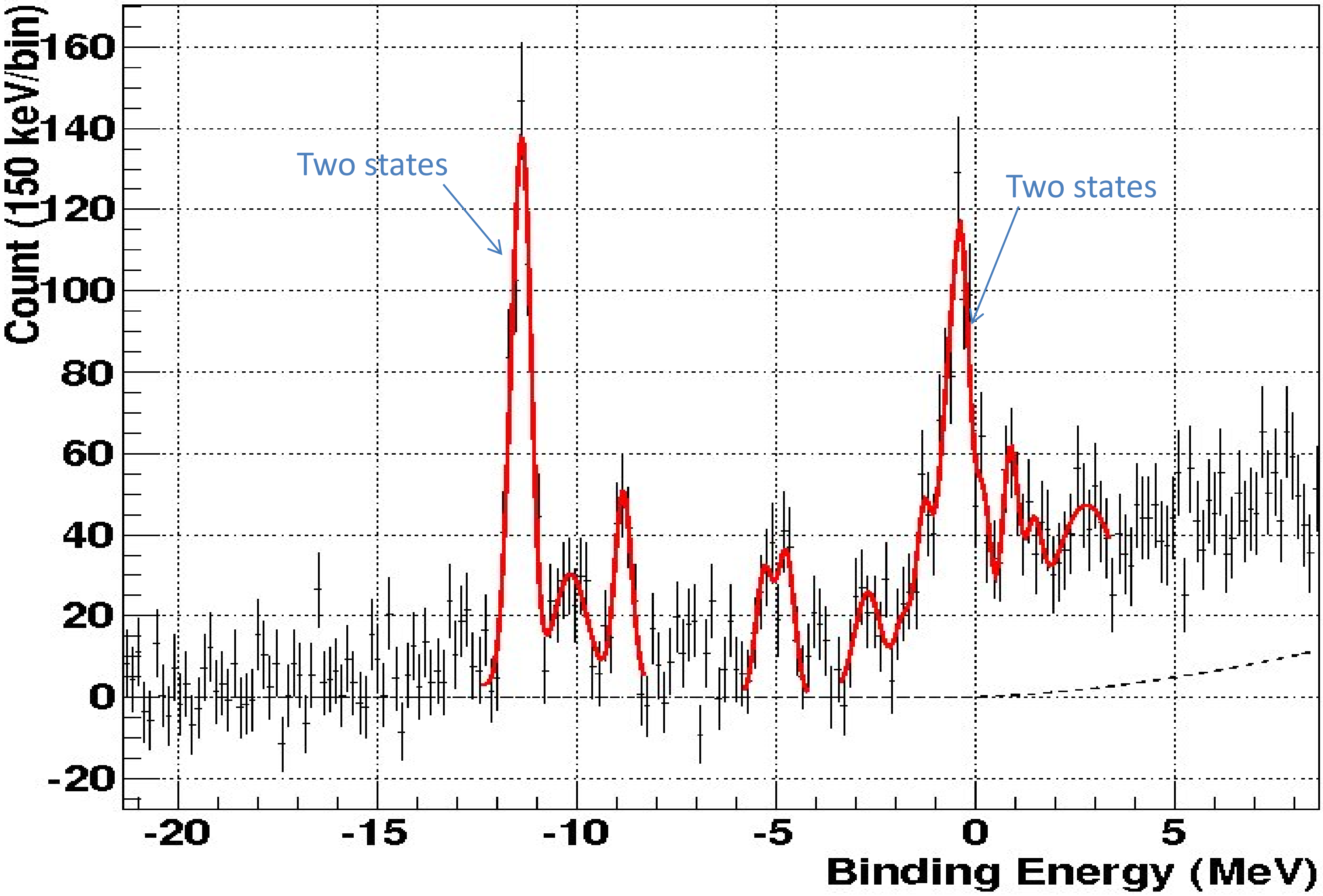
A Naïve theory does not explain the experimental result.



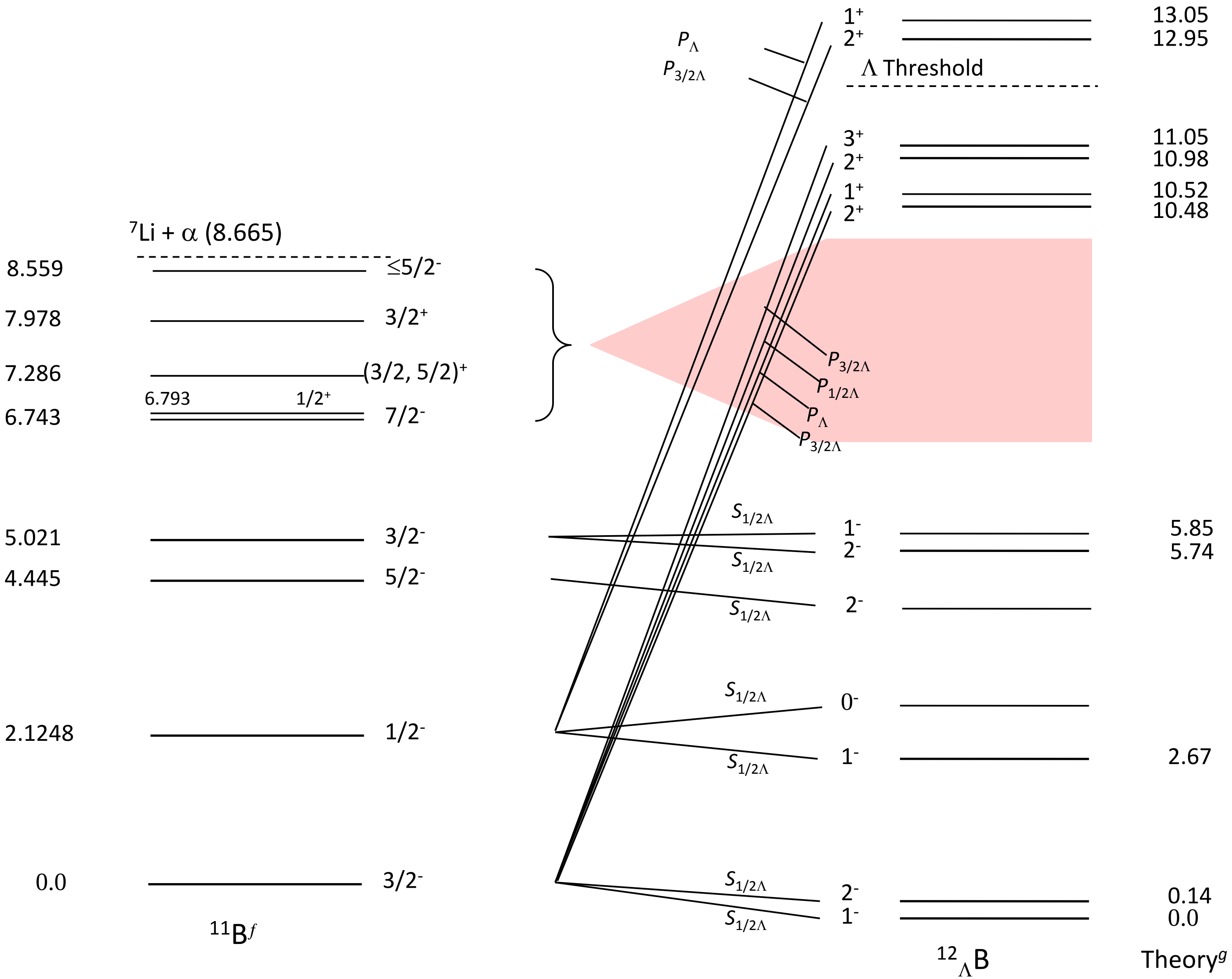


A Naïve calculation on CSB effect, which explains ${}^{4}_{\Lambda}$H – ${}^{4}_{\Lambda}$He and available s, p-shell hypernuclear data , gives opposite shifts to A=7 ,T=1 iso-triplet Λ Hypernuclei.

Highlight: The New $^{12}{}_{\Lambda}B$ Spectroscopy



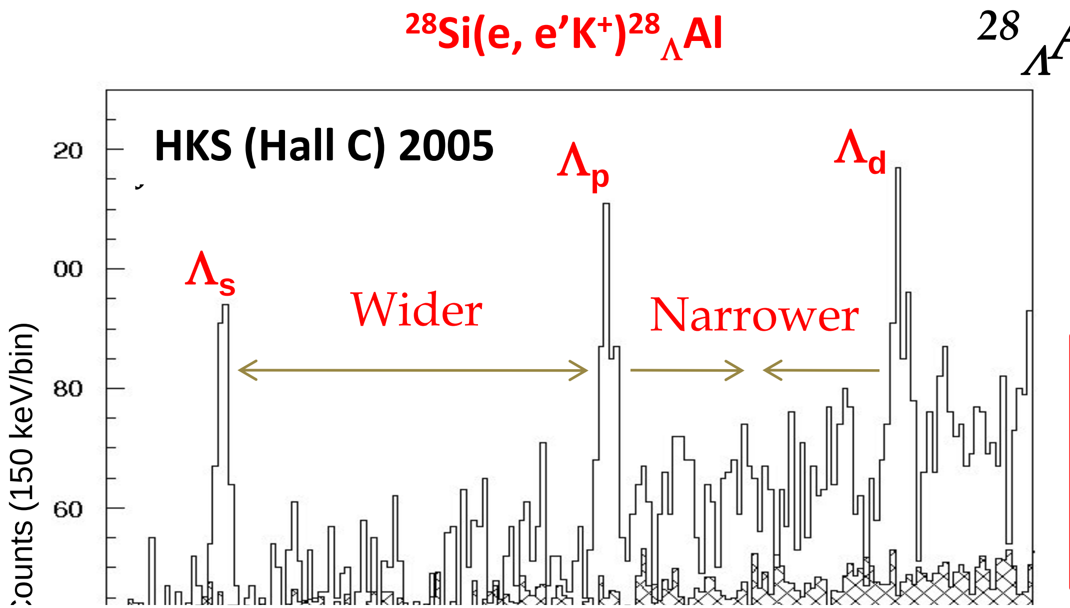
The Expected $^{12}{}_{\Lambda}B$ Spectroscopy



f F. AJZENBERG-SELOVE and C. L. BUSCH, *Nuclear Phystcs* A336 (1980) 1-154.

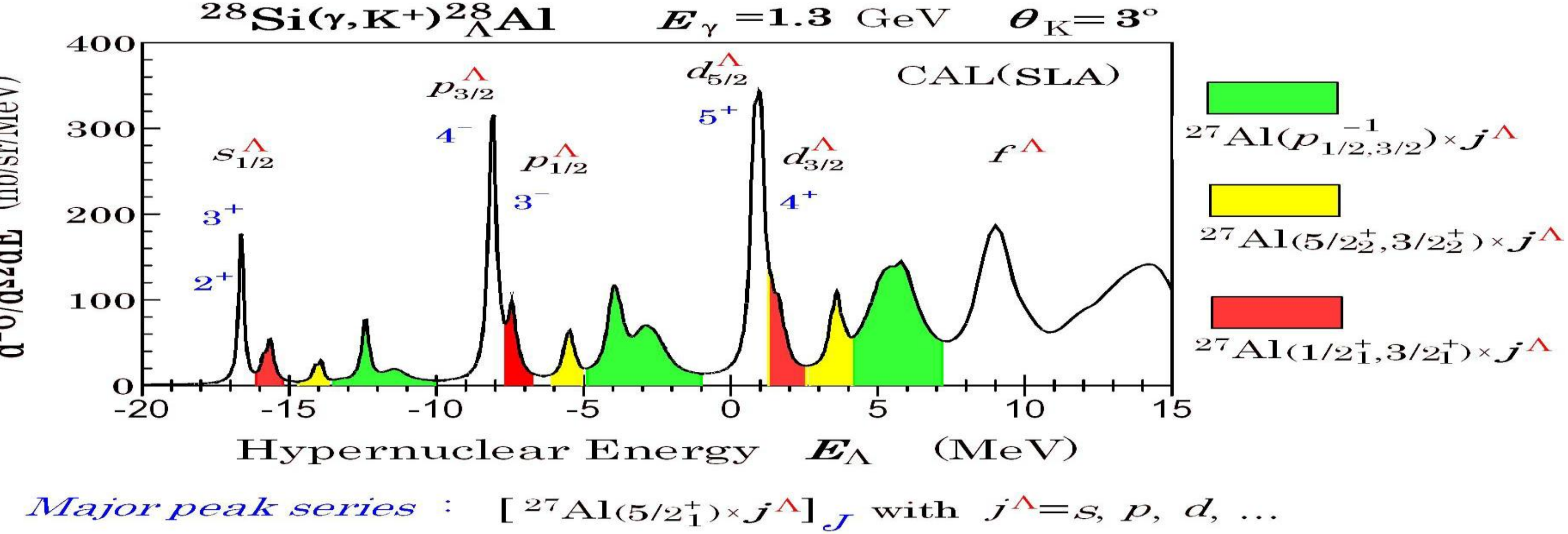
g D.J. Millener, *Nuclear Phystcs* A691 (2001) 93c. P_Λ means a mixing of 1/2 and 3/2 states.

Highlights: Spectroscopy of $^{28}{}_{\Lambda}$Al



- 1st observation of $^{28}{}_{\Lambda}$Al
- ~400 keV FWHM resol.
- Clean observation of the shell structures

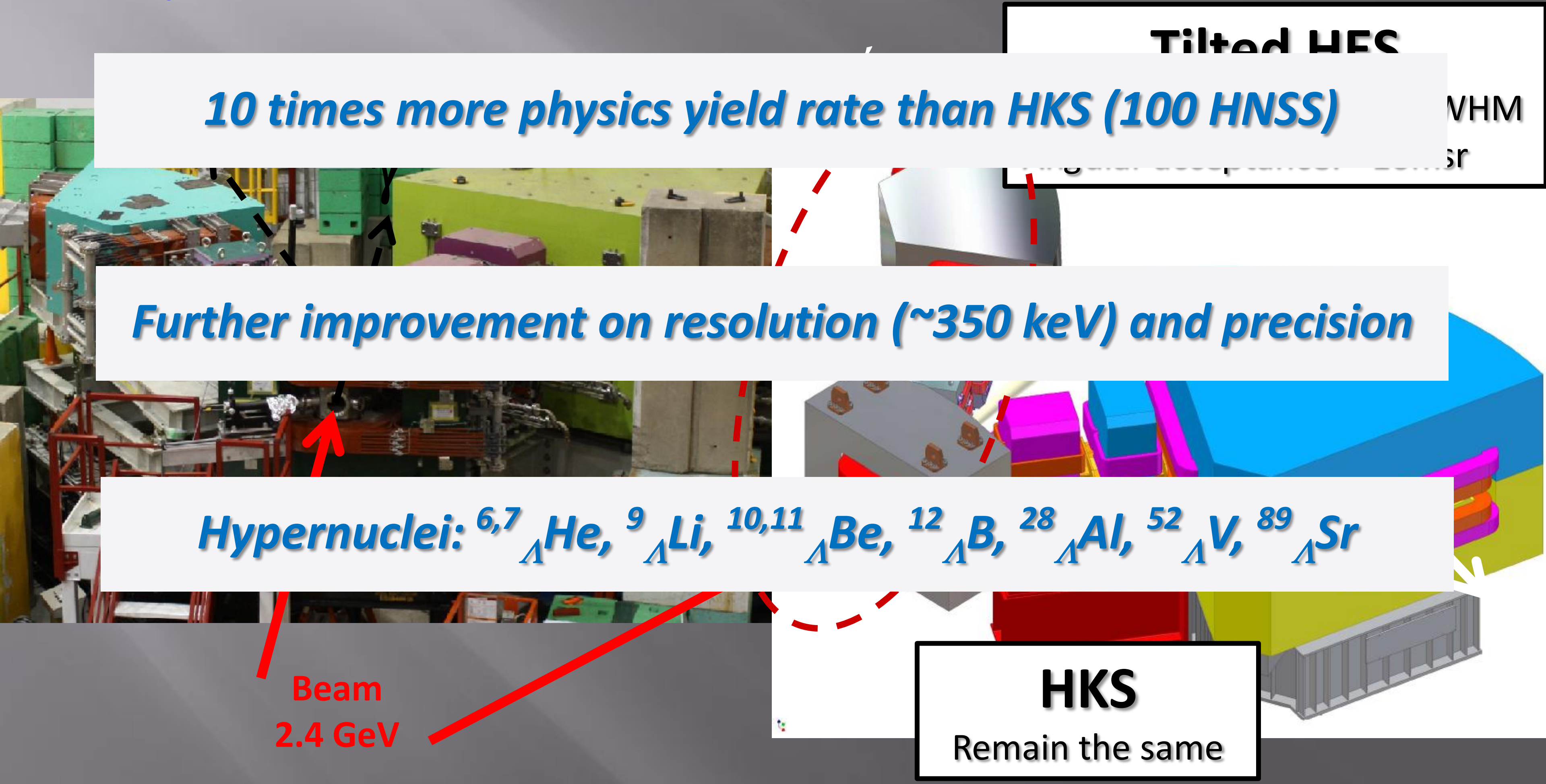
Peak	B_{Λ}(MeV)	E_x(MeV)	Errors (St.	Sys.)
#1	-17.820	0.0	± 0.027	± 0.135
#2	-6.912	10.910	± 0.033	± 0.113
#3	1.360	19.180	± 0.042	± 0.105



Major peak series : [^{27}Al($5/2^{+}_{1}$)×j^{Λ}]$_J$ with j^{Λ}=s, p, d, ...

Hypernuclear Physics Programs in Hall C

- **E05-011/HKS-HES (Phase III, 2009) – Second upgrade**
- **Replaced Enge by new HES spectrometer for the electron arm**



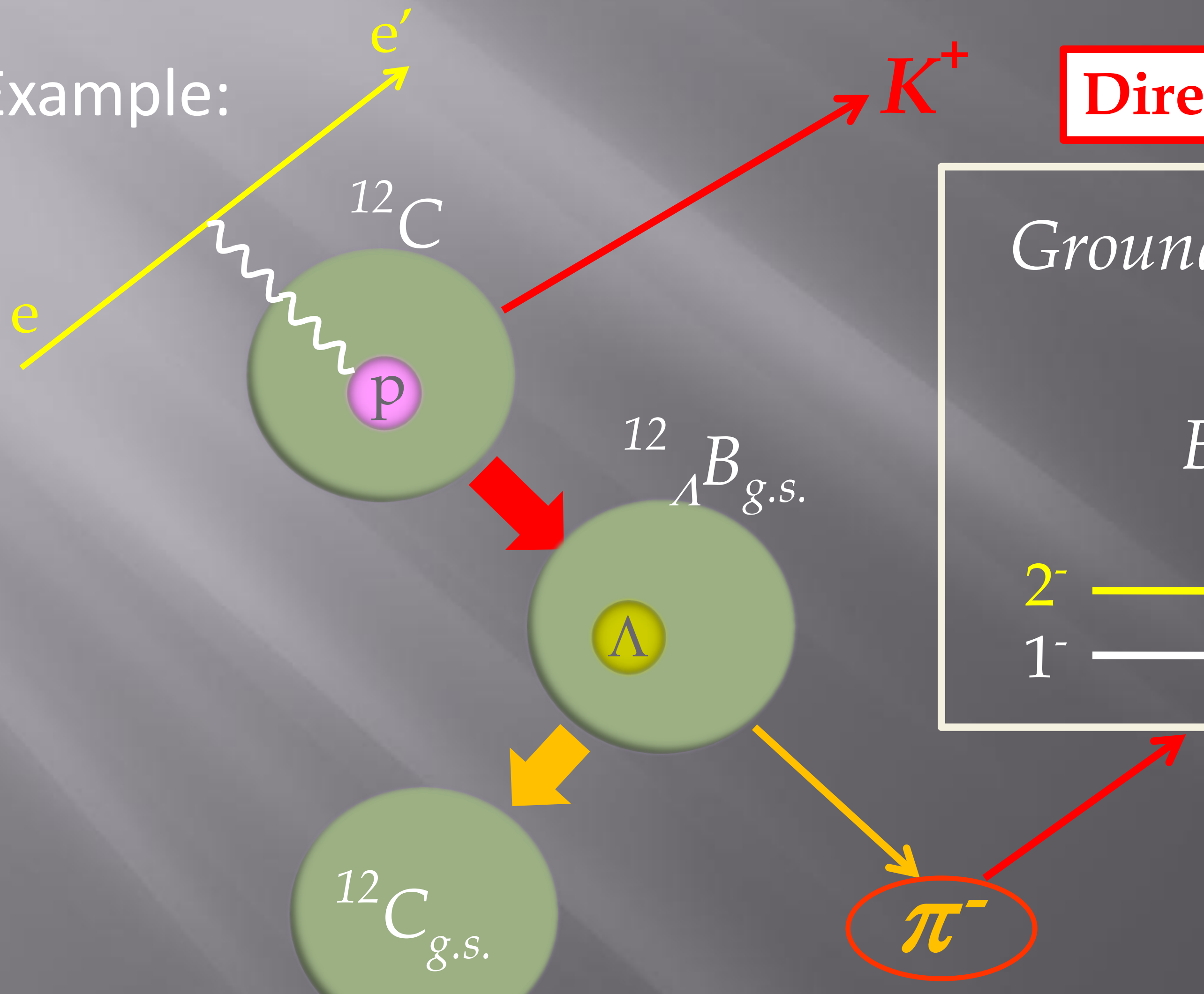
10 times more physics yield rate than HKS (100 HNSS)

Further improvement on resolution (~350 keV) and precision

Hypernuclei: $^{6,7}{}_{\Lambda}$He, $^{9}{}_{\Lambda}$Li, $^{10,11}{}_{\Lambda}$Be, $^{12}{}_{\Lambda}$B, $^{28}{}_{\Lambda}$Al, $^{52}{}_{\Lambda}$V, $^{89}{}_{\Lambda}$Sr

Decay Pion Spectroscopy for Light and Exotic Λ-Hypernuclei

Example:



Direct Production

Ground state doublet
of $^{12}_{\Lambda}B$
B_{Λ} *and* τ

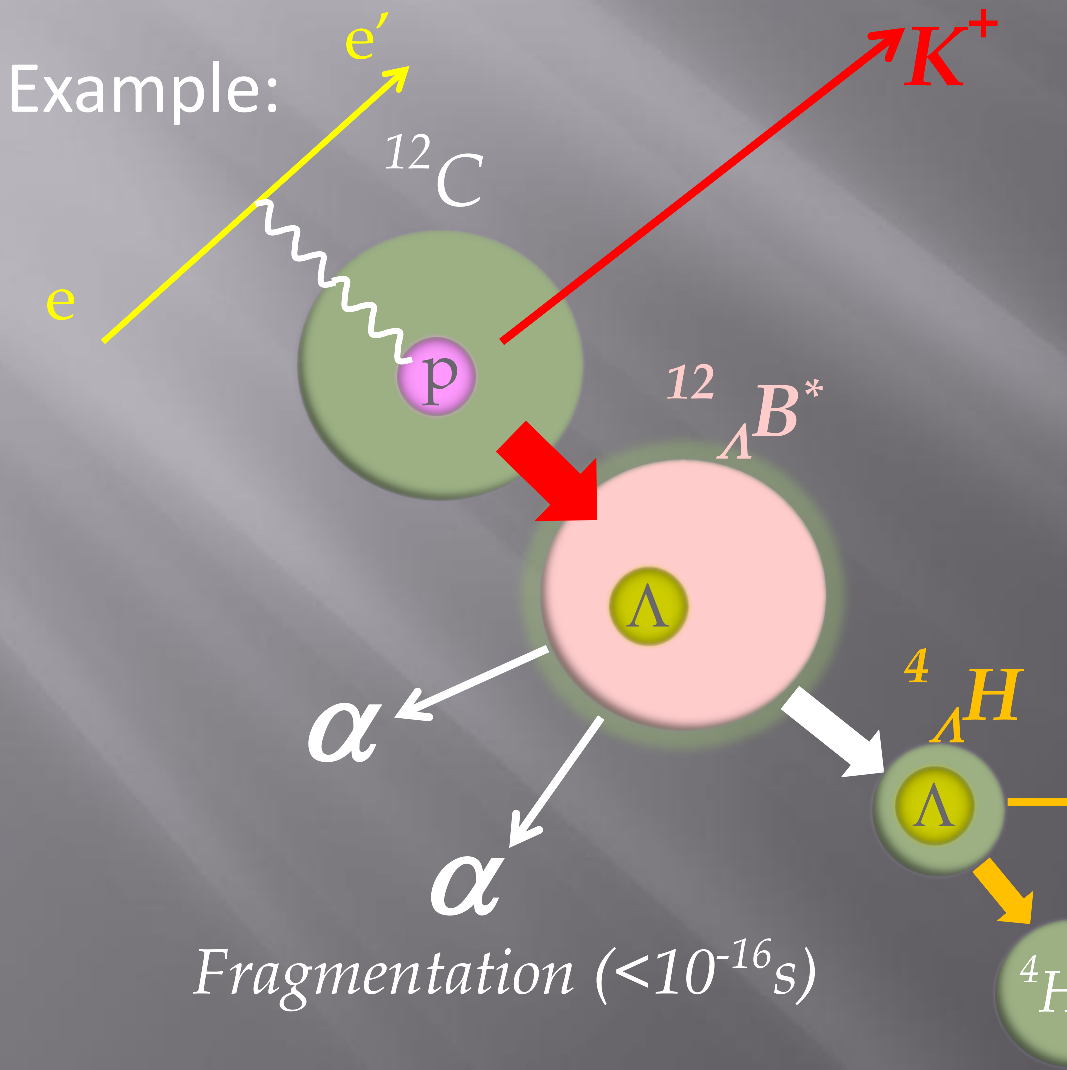
2^- ~150 keV
1^- 0.0

Weak mesonic two body decay

Decay Pion Spectroscopy for Light and Exotic Λ-Hypernuclei

Fragmentation Process

Example:

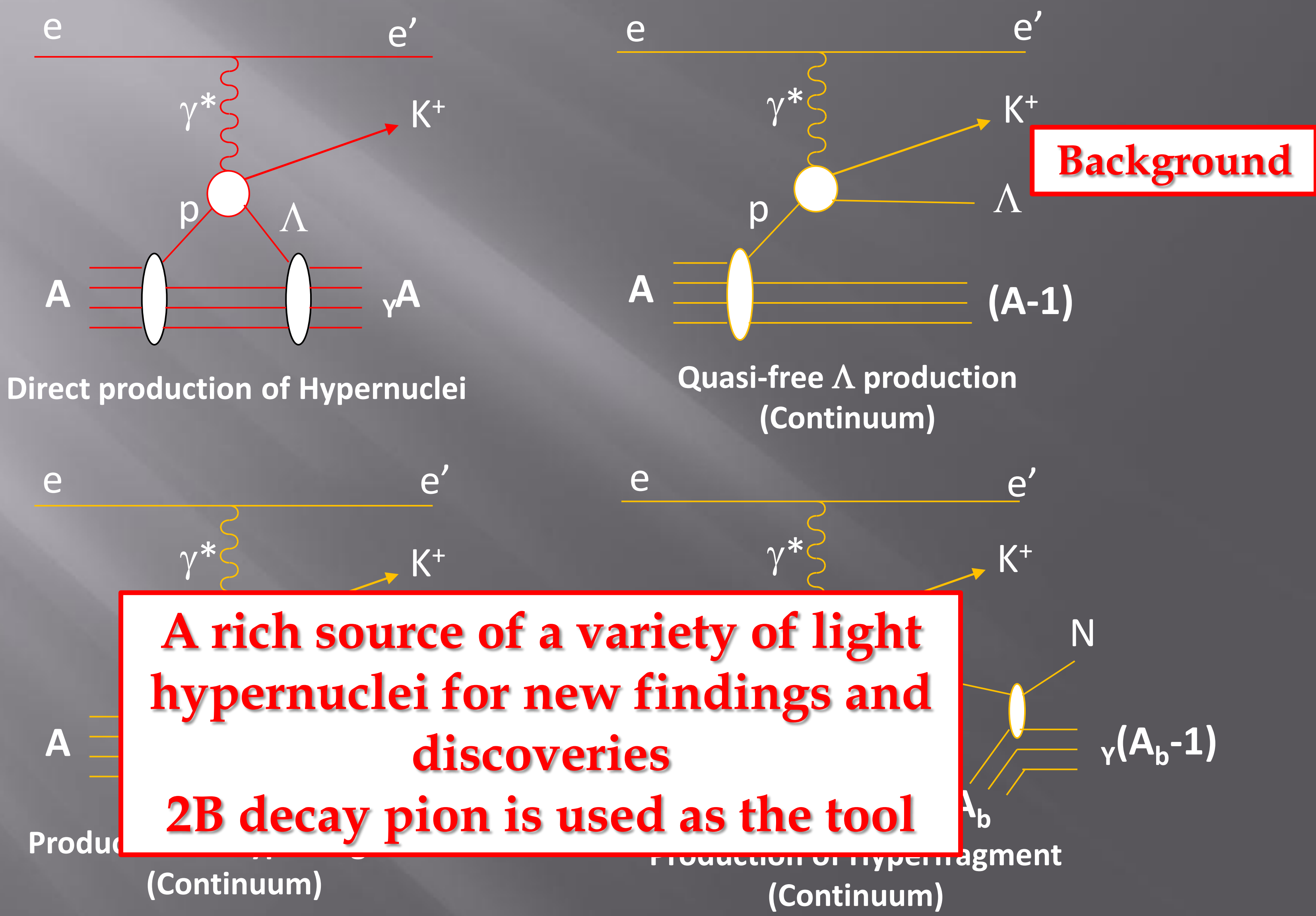


Fragmentation (<10^{-16}s)

Access to variety of light and exotic hypernuclei, some of which cannot be produced or measured precisely by other means

Weak mesonic two body decay (~10^{-10}s)

Electro-production of Hypernuclei and Hyperfragments from the Continuum



Direct production of Hypernuclei

Quasi-free Λ production (Continuum)

Background

Produc

(Continuum)

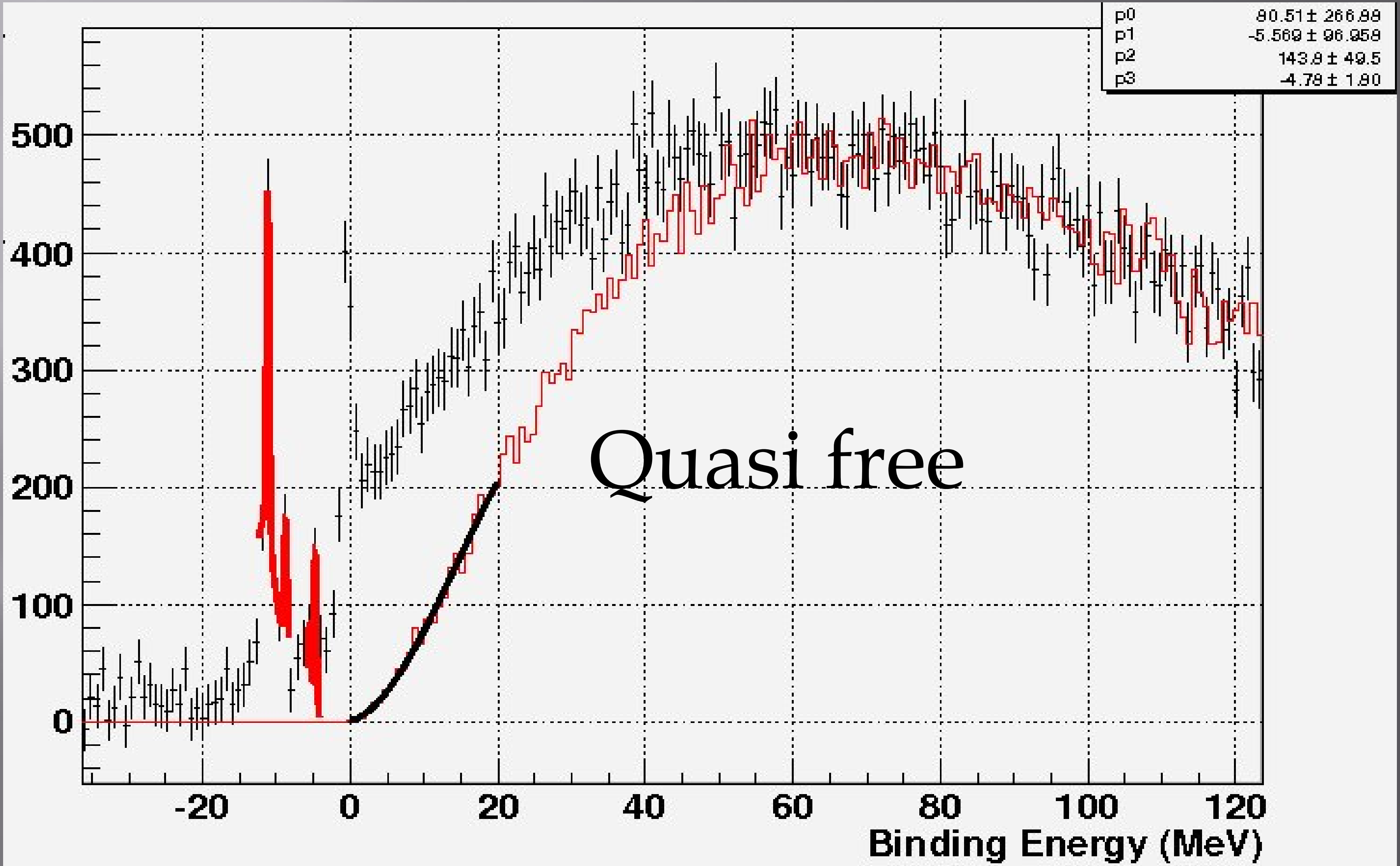
Production of Hyperfragment (Continuum)

A rich source of a variety of light hypernuclei for new findings and discoveries

2B decay pion is used as the tool

Example: $^{12}_{\Lambda}B$ Production w/ (e, e' K^+)

w/o e' tagging, GF rate is 3 times more (kinematics acceptance)

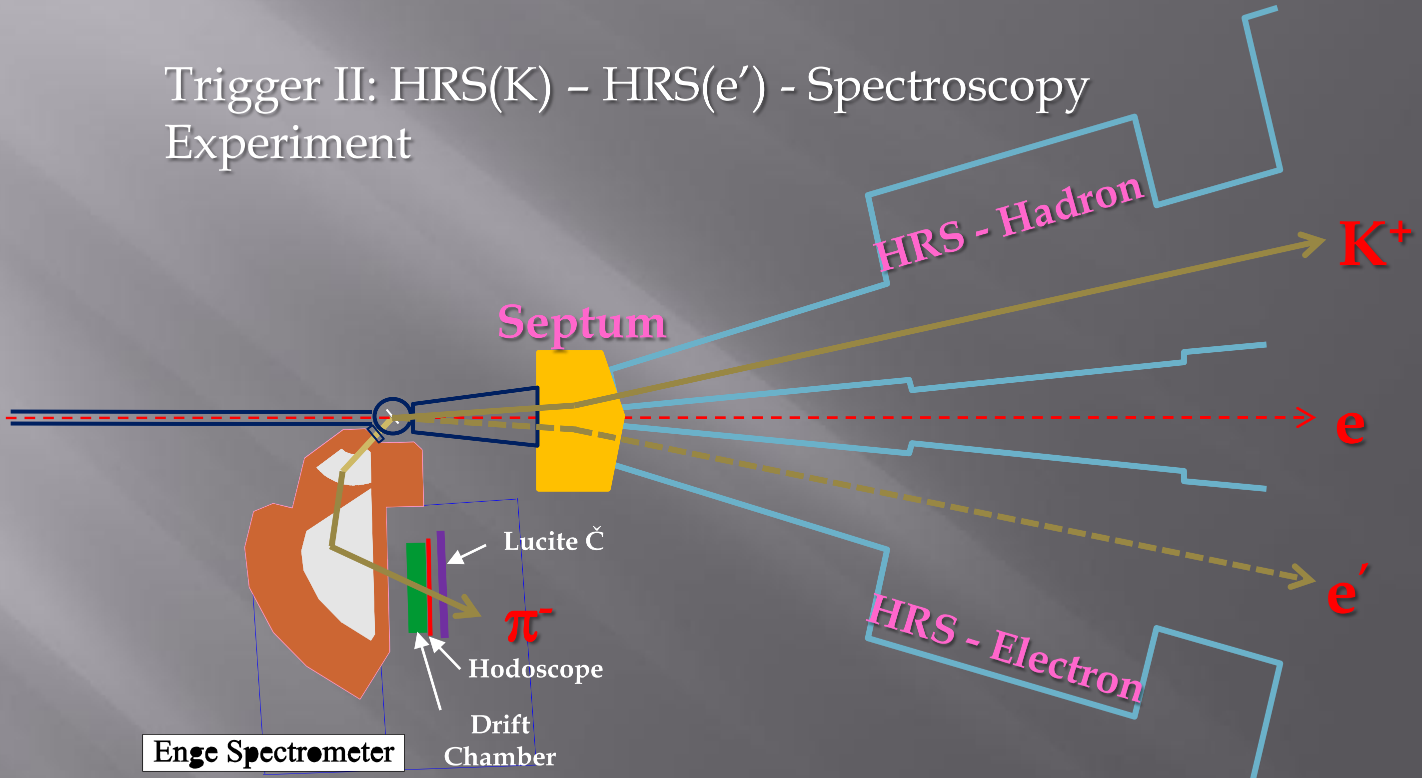


Decay Pion Spectroscopy for Light and Exotic Λ-Hypernuclei

- High precision on ground state light hypernuclei
  - Resolution: ~130 keV FWHM;   mass precision : < ±30 keV
  - Precise Λ binding energy
  - Charge symmetry breaking
- Linkage between structures of *hypernuclei* and *nuclei*
  - Determining ground state spin/parity
- Search for Isomeric low lying states (*Isomerism*)
- Study the drip line limit on Λ-hypernuclei, such as heavy hyper-hydrogen: $^{6}_{\Lambda}H$, $^{7}_{\Lambda}H$, *and* $^{8}_{\Lambda}H$
- Medium modification of baryon property

Hall A Experimental Layout

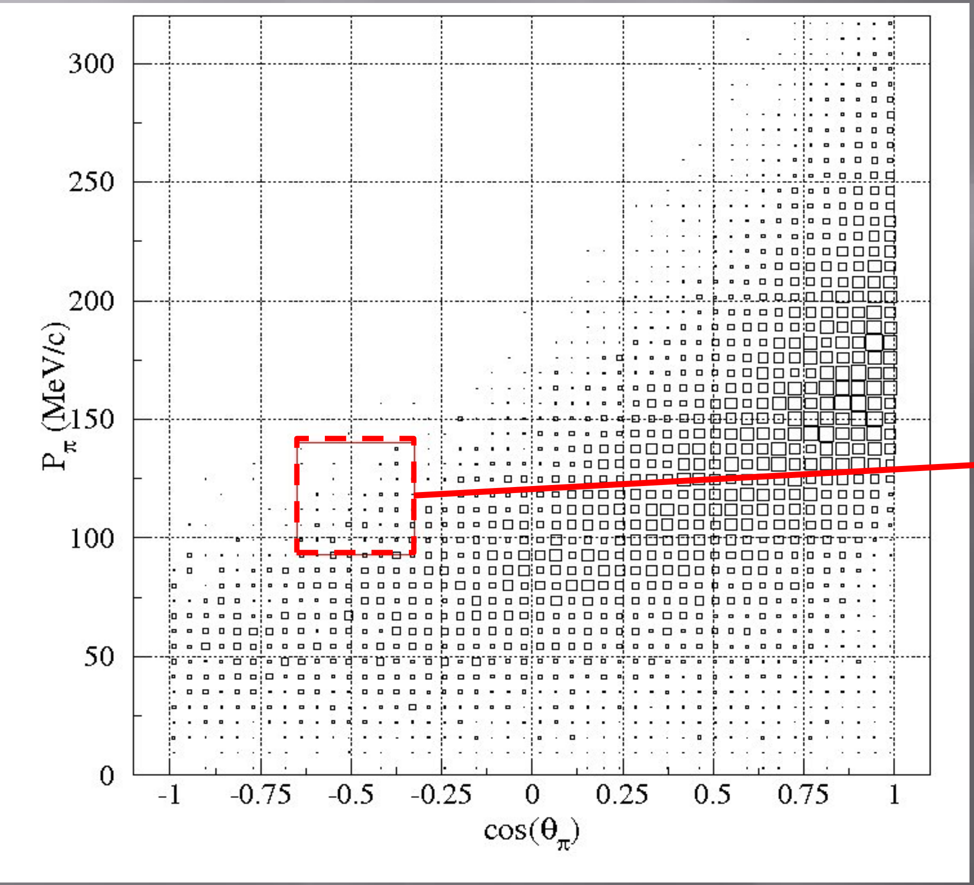
Trigger II: HRS(K) – HRS(e′) - Spectroscopy Experiment



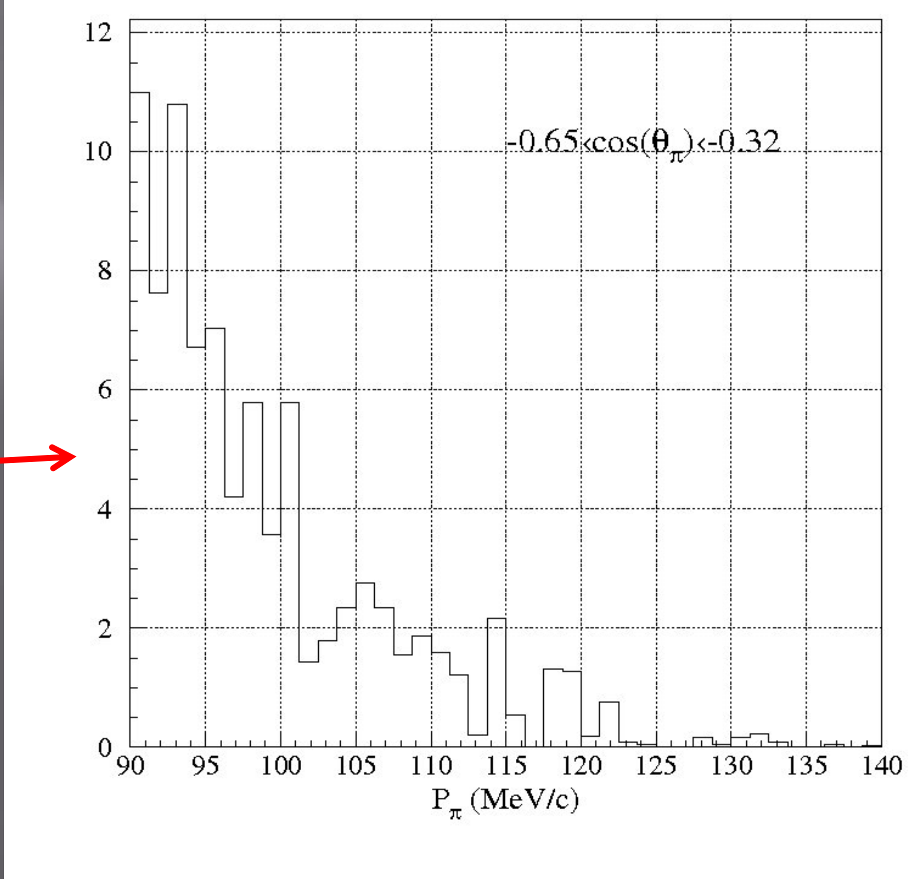
Trigger I: HRS(K) – Enge(π) - Decay Pion Experiment

Free of Q.F. Λ Background

Quasi-free $\Lambda \rightarrow p + \pi^-$ (all)

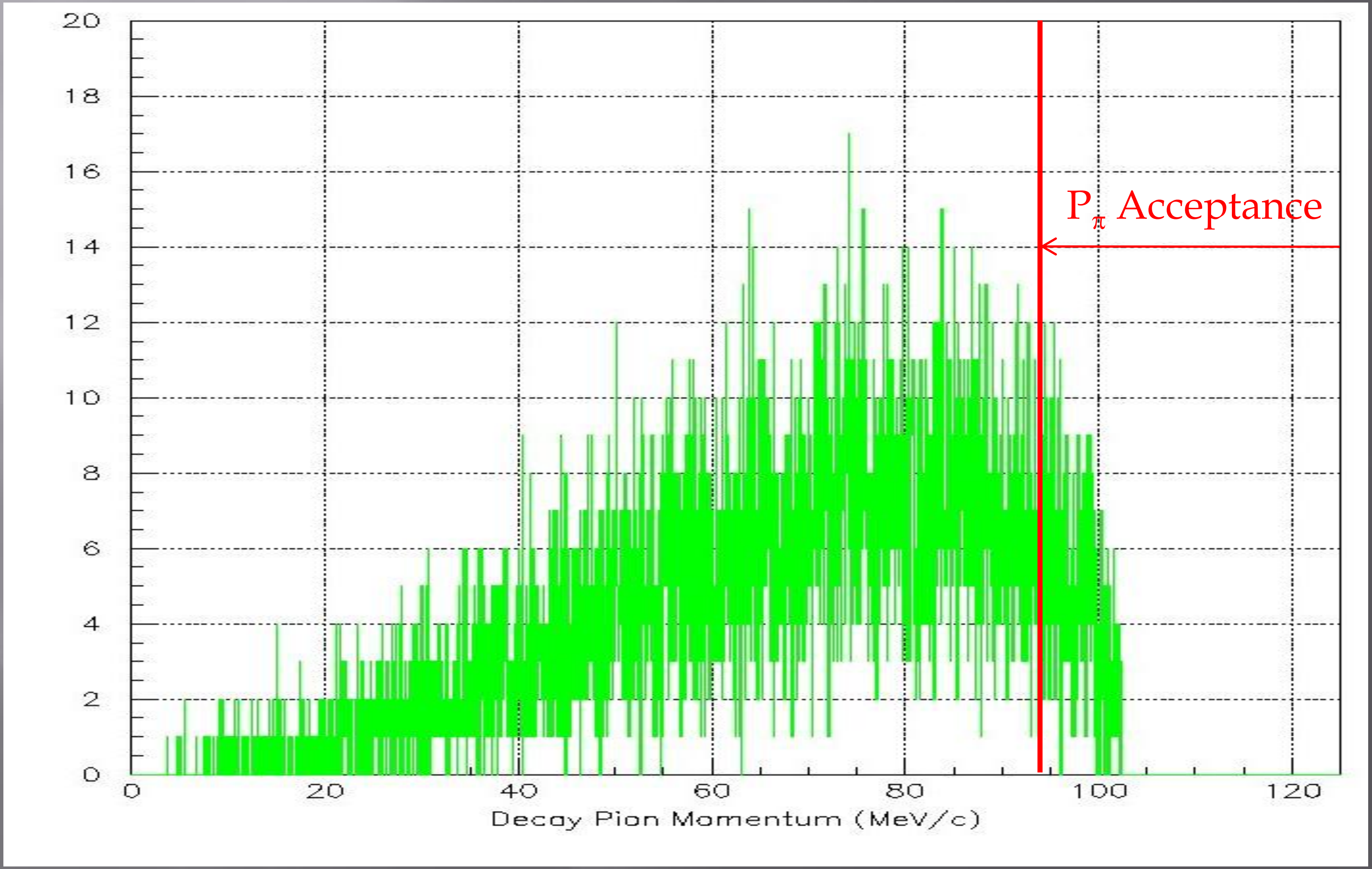


Within the HES acceptances



Three-Body Decay Background

Example: ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + p + \pi^{-}$



Hypernuclei from a ^{7}Li Target

Two-Body decay – 6 possible hypernuclei

Breakup Mode	Q value (MeV)	π^- Decay	P_π (MeV/c)	Width (keV/c) FWHM
$^{7}_{\Lambda}$He	-	^{7}Li + π^-	114.61	165
p + $^{6}_{\Lambda}$H	-23.503 (B_Λ=5.1)	^{6}He + π^-	133.47	165
n + $^{6}_{\Lambda}$He	-3.409	^{6}Li + π^-	108.39	165
d + $^{5}_{\Lambda}$H	-23.011 (B_Λ=4.1)	^{5}He + π^-	133.42	~900*
^{3}H + $^{4}_{\Lambda}$H	-16.995	^{4}He + π^-	132.95	165
^{4}H + $^{3}_{\Lambda}$H	-26.981	^{3}He + π^-	114.29	165

Three-Body decay – Background

Breakup Mode	Q value (MeV)	π^- Decay	P_π max (MeV/c) – cut off
d + $^{5}_{\Lambda}$H	-23.011 (B_Λ=4.1)	^{4}He + n + π^-	139.27*
2n + $^{5}_{\Lambda}$He	-3.567	^{4}He + p + π^-	102.42
3n + $^{4}_{\Lambda}$He	-24.868	^{3}He + p + π^-	103.15

Hypernuclei from a ^{9}Be Target

Two-Body decay – 6 additional hypernuclei

Breakup Mode	Q value (MeV)	π^- Decay	P_π (MeV/c)	Width (keV/c) FWHM
$^{9}_{\Lambda}$Li	-	^{9}Be + π^-	121.18	165
p + $^{8}_{\Lambda}$He	-13.817	^{8}Li + π^-	116.40	165
n + $^{8}_{\Lambda}$Li	-3.756	^{8}Be + π^-	124.12	165
2p + $^{7}_{\Lambda}$H	-40.328 (B_Λ=6.1)	^{7}He + π^-	135.17	~270*
d + $^{7}_{\Lambda}$He	-12.568	^{7}Li + π^-	114.61	165§
2n + $^{7}_{\Lambda}$Li	-12.218	^{7}Be + π^-	108.02	165
^{3}He + $^{6}_{\Lambda}$H	-29.608 (B_Λ=5.1)	^{6}He + π^-	133.47	165§
^{3}H + $^{6}_{\Lambda}$He	-9.745	^{6}Li + π^-	108.39	165§
3n + $^{6}_{\Lambda}$Li	-18.957	^{6}Be + π^-	100.58	~220**
α + $^{5}_{\Lambda}$H	-11.749 (B_Λ=4.1)	^{5}He + π^-	133.42	~900*§
n + α + $^{4}_{\Lambda}$H	-12.005	^{4}He + π^-	132.95	165§
^{6}He + $^{3}_{\Lambda}$H	-18.183	^{3}He + π^-	114.29	165§

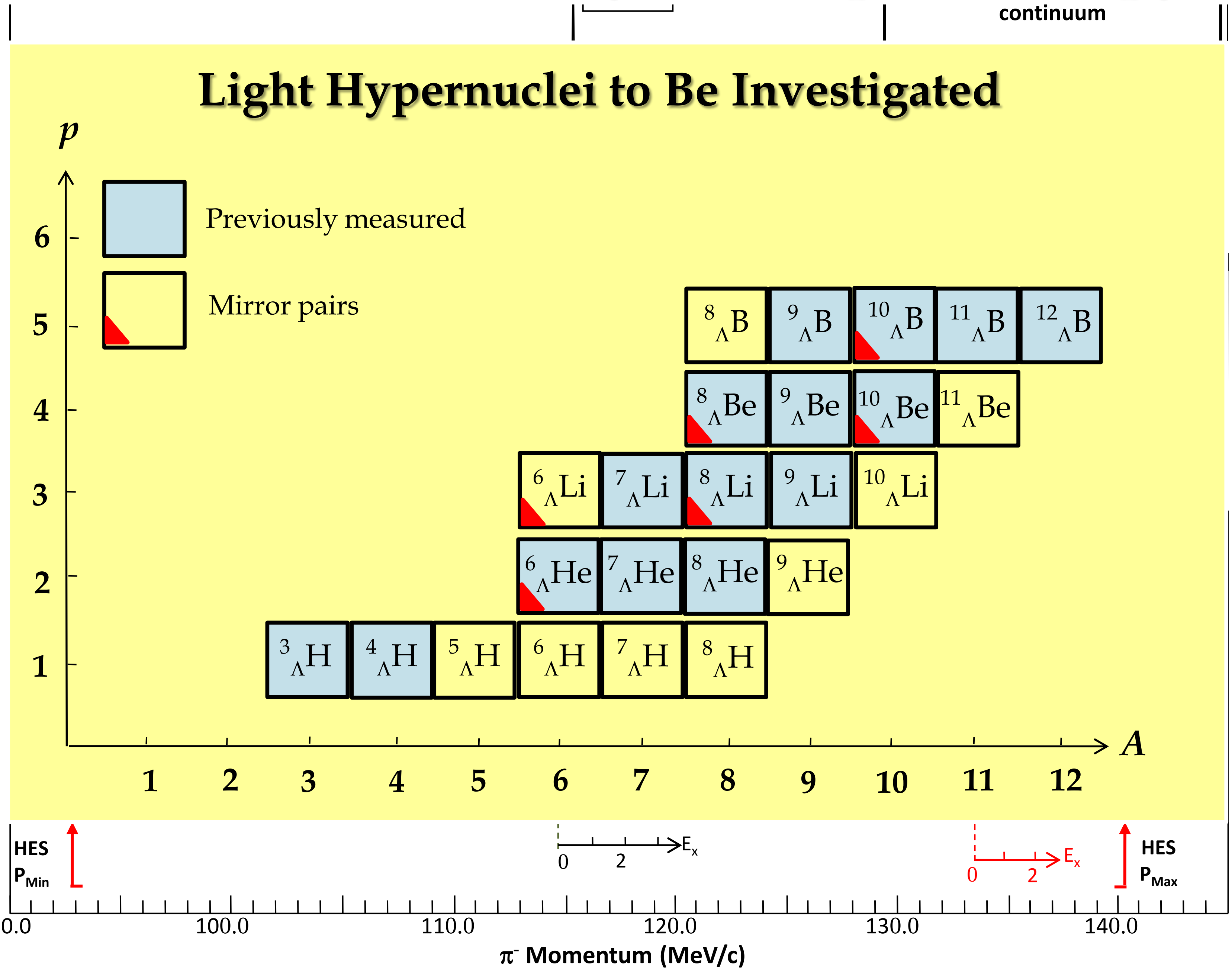
Hypernuclei from a ^{12}C Target

Two-Body decay – 12 additional hypernuclei

Breakup Mode	Q value (MeV)	π^- Decay	P_π (MeV/c)	Width (keV/c) FWHM
$^{12}_{\Lambda}$B	-	^{12}C + π^-	115.49	165
p + $^{11}_{\Lambda}$Be	-12.280 (B_Λ=10.5)	^{11}B + π^-	109.66	165
n + $^{11}_{\Lambda}$B	-12.765	^{11}C + π^-	105.99	165
2p + $^{10}_{\Lambda}$Li	-32.908 (B_Λ=12.3)	^{10}Be + π^-	119.78	165
d + $^{10}_{\Lambda}$Be	-18.264	^{10}B + π^-	104.31	165
2n + $^{10}_{\Lambda}$B	-22.544	^{10}C + π^-	95.84	165
3p + $^{9}_{\Lambda}$He	-48.534 (B_Λ=7.8)	^{9}Li + π^-	117.83	165
^{3}He + $^{9}_{\Lambda}$Li	-30.237	^{9}Be + π^-	121.18	$165^{\S}$
^{3}H + $^{9}_{\Lambda}$Be	-16.072	^{9}B + π^-	96.88	165^{*}
3n + $^{9}_{\Lambda}$B	-41.713	^{9}C + π^-	96.71	165
4p + $^{8}_{\Lambda}$H	-68.937 (B_Λ=7.1)	^{8}He + π^-	137.15	165
^{4}Li + $^{8}_{\Lambda}$He	-46.961	^{8}Li + π^-	116.40	$165^{\S}$
α + $^{8}_{\Lambda}$Li	-14.444	^{8}Be + π^-	124.12	$165^{\S}$
^{4}H + $^{8}_{\Lambda}$Be	-37.659	^{8}B + π^-	97.09	165
4n + $^{8}_{\Lambda}$B	-56.317 (B_Λ=6.7)	^{8}C + π^-	97.21	365^{**}
p + ^{4}Li + $^{7}_{\Lambda}$H	-73.473 (B_Λ=6.1)	^{7}He + π^-	135.17	~$270^{*\S}$
^{5}Li + $^{7}_{\Lambda}$He	-26.436	^{7}Li + π^-	114.61	$165^{\S}$
^{5}He + $^{7}_{\Lambda}$Li	-25.782	^{7}Be + π^-	108.02	$165^{\S}$
^{6}Be + $^{6}_{\Lambda}$H	-48.317 (B_Λ=5.1)	^{6}He + π^-	133.47	$165^{\S}$
^{6}Li + $^{6}_{\Lambda}$He	-24.186	^{6}Li + π^-	108.39	$165^{\S}$
^{6}He + $^{6}_{\Lambda}$Li	-27.663	^{6}Be + π^-	100.58	~$220^{**\S}$
^{7}Be + $^{5}_{\Lambda}$H	-44.499 (B_Λ=4.1)	^{5}He + π^-	133.42	~$900^{*\S}$
2α + $^{4}_{\Lambda}$H	-22.693	^{4}He + π^-	132.95	$165^{\S}$
^{9}Be + $^{3}_{\Lambda}$H	-27.244	^{3}He + π^-	114.29	$165^{\S}$

Illustration of Decay Pion Spectroscopy

Light Hypernuclei to Be Investigated



Summary

- High quality and high intensity CW CEBAF beam at JLAB made high precision hypernuclear programs possible
- Electroproduced hypernuclei are neutron rich and have complementary features to those produced by mesonic beams. Together with J-PARC's new programs, as well as those at other facilities around world, the hypernuclear physics will have great achievement in the next couple of decades
- The mass spectroscopy program will continue beyond JLAB 12 GeV upgrade
- The new decay pion spectroscopy program will start a new frontier